TRANSIENT EMISSIONS TESTING OF BIODIESEL AND OTHER ADDITIVES IN A DDC SERIES 60 ENGINE

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FINAL REPORT

Prepared for

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EXECUTIVE SUMMARY

A test program was conducted at Southwest Research Institute (SwRI) on behalf of the National Biodiesel Board (NBB) to evaluate the effects of several diesel fuel additives, including biodiesel, on exhaust emissions for a rebuilt, four-stroke 1991 Detroit Diesel Series 60 engine. Additized fuels were made from emission grade diesel fuel, and they were evaluated using hot-start testing over the EPA heavy-duty transient test cycle. Emissions data were generated using five different additized fuels (referred to as Fuels A, B, C, D, and E) and two "reference" fuels; an emissions grade, low-sulfur 2-D diesel fuel (R1), and a low sulfur, low aromatic diesel fuel intended to approximate a California reference diesel fuel (R2). Regulated emissions of HC, CO, NO_x, and particulates were measured, as well as unregulated emissions of SOF and sulfates. On selected test runs, hydrocarbon speciation was performed to characterize the individual compounds that make up total gaseous HC emissions.

All of the additives, except for the cetane improver (DTBP), were oxygenates. The oxygen levels and cetane numbers of the fuels are summarized in the table, along with average hot-start emissions levels obtained for each additized fuel (A, B, C, D, & E) and the two reference fuels (R1, R2). The low aromatic reference fuel (R2) was tested in order to evaluate the potential use of the additives in diesel fuel for California. Compared to the baseline 2-D fuel, the low aromatic fuel had substantially lower NO_x emissions but slightly higher particulate emissions.

All the additized fuels had lower particulate than either the low aromatic fuel or the 2-D reference fuel. None of the candidate blends produced NO_x emissions as low as the low aromatic fuel. All three oxygenate additives achieved reductions in particulate and CO compared to the levels observed for 2-D reference fuel (R1). The amount of reduction depended on the amount of oxygen in the fuel. Biodiesel, at a 20 percent blend level in Fuel C, contained about 2.2 percent oxygen by weight and reduced both CO and particulates by 10 percent. Both DTBG and TPM were blended at a much lower concentration, resulting in less oxygen in the fuel, and therefore smaller particulate reductions. When biodiesel and DTBG were combined (Fuel D), their effects on emissions were cumulative such that the combination was associated with greater reductions in particulates and CO than obtained with either of the two additives used separately, likely due to the higher level of oxygen in the fuel. Speciation of gaseous hydrocarbon emissions indicated that none of the oxygenate additives caused any significant changes in toxic or reactive hydrocarbon species. Analysis of the total particulate from all runs indicated that observed particulate reductions with various oxygenates occurred within the carbon or "dry" soot portion of the particulate. Although, a dry soot reduction was observed when biodiesel was used, biodiesel was associated with an increase in SOF of the total particulate for Fuels C and D.

The use of DTBP as a cetane improver was planned to offset the small NO_x increase expected from using biodiesel. However, the transient emission test results indicated no increase in NO_x emissions when biodiesel was used. Therefore, when the cetane improver was used in B20 (Fuel E), NO_x emissions decreased about 5 percent below the baseline 2-D level. In addition, the reductions in CO and particulates attributed to biodiesel were unaffected by the use of the cetane improver, although SOF was reduced. The net result was

That Fuel E decreased both NO_x and particulates somewhat compared to Fuel R1. With B20, HC and SOF tended to increase, but with cetane improver, levels of these pollutants were reduced or kept near baseline levels. The net result was that B20 with cetane improver had HC, CO, and PM emission levels below both reference fuels (R1, R2) and it produced a NO_x level above that obtained with the low aromatic fuel (R2), but below the levels obtained with the other fuels.

EXECUTIVE SUMMARY TABLE. AVERAGE HOT-START EMISSIONS

Fuel	Description	Oxygen, %	Cetane No.		Transient Emissions, g/hp-hr				SOF, g/hp-hr	Sulfate, g/hp-hr	BSFC, lb/hp-hr	Work hp-hr
					HC	CO	NO$_x$	PM				
R1	Baseline, 2-D	0	45.8	Mean	0.077	2.258	4.679	0.220	0.065	0.003	0.384	25.0
				Std. Dev.	0.004	0.039	0.065	0.005	0.005	<0.001	0.006	0.25
A	R1 + DTBG	0.5	44.9	Mean	0.083	2.239	4.677	0.209	0.066	0.003	0.387	25.1
				Std. Dev.	0.009	0.030	0.072	0.004	0.005	<0.001	0.006	0.09
B	R1 + TPM	0.6	45.4	Mean	0.074	2.245	4.676	0.213	0.063	0.003	0.397	25.2
				Std. Dev.	0.009	0.030	0.030	0.001	0.004	<0.001	0.004	0.04
C	R1 + Biodiesel	2.2	48.1	Mean	0.095	2.052	4.644	0.200	0.075	0.002	0.402	25.1
				Std. Dev.	0.028	0.031	0.036	0.008	0.006	<0.001	0.003	0.09
D	R1 + Biodiesel +DTBG	2.7	47.3	Mean	0.109	2.031	4.626	0.194	0.082	0.002	0.400	25.2
				Std. Dev.	0.021	0.026	0.089	0.005	0.004	<0.001	0.001	0.02
R2	Low Aromatic Diesel	0	50.5	Mean	0.087	2.144	4.179	0.223	0.067	0.001	0.385	25.1
				Std. Dev.	0.006	0.048	0.071	0.009	0.004	<0.001	0.002	0.08
E	R1 + Biodiesel + DTBP	2.2	60.4	Mean	0.073	1.798	4.387	0.200	0.067	0.002	0.399	25.0
				Std. Dev.	0.007	0.055	0.057	0.008	0.006	<0.001	0.008	0.03

I. INTRODUCTION

This final report contains the results of a test program conducted on behalf of the National Biodiesel Board (NBB). The objective of this test program was to evaluate several diesel fuel additives, both by themselves and in conjunction with biodiesel, in terms of their effects on diesel exhaust emissions. The fuel additives were produced and supplied by ARCO Chemical Company. Fuel blends containing one or more additives were evaluated against both a 1994 low-sulfur 2-D diesel fuel, and a low aromatic diesel fuel. The evaluations were conducted using a 1991 Detroit Diesel Corporation Series 60 engine, and were performed following a protocol similar to that used for qualifying diesel fuels for sale in California under CARB regulations.

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II. DESCRIPTION OF PROGRAM

A. Test Engine

The engine tested was a rebuilt 1991 DDC Series 60, which was a four-stroke, turbocharged, six-cylinder engine of in-line configuration. The test engine had 12.7 liters displacement, and it was nominally rated at 370 horsepower at an engine speed of 1800 rpm. Peak torque was 1450 lb-ft at an engine speed of 1200 rpm. Engine control was achieved by means of a throttle potentiometer supplied by DDC to provide an interface between the electronic control system of the engine and the SwRI servo controller. The engine electronic control system was a standard DDEC II electronic control module, as is typically used with the Series 60 engine. Transient test cell installation of the Series 60 engine is shown in Figure 1.

FIGURE 1. TRANSIENT TEST CELL INSTALLATION OF THE REBUILT 1991 DDC SERIES 60 ENGINE

B. Test Fuels and Oil

A number of fuels were tested during this program. The baseline fuel used for blending the five additional fuels was an emissions grade 2-D diesel obtained from Phillips Petroleum, Lot No. R-851 and coded SwRI EM-1852-F. This baseline or "reference" fuel is referred to in this report as R1. Descriptions of various test blends or "additized" fuels, designated A, B, C, D, and E, are given below in Table 1. A second reference fuel, designated

R2 was also used during this program, and this fuel was intended to approximate a low aromatic CARB reference diesel fuel. Fuel R2 was obtained through ARCO from Howell Hydrocarbons, and coded SwRI EM-1720-F. The lubricating oil used in the Series 60 engine was a 15W-40 produced by Mobil.

Properties for all test fuels are given in Table 2. Fuel R2 had very low sulfur at 0.011 percent. Baseline fuel, R1, had 0.032 percent sulfur and Fuels C, D, and E had lower sulfur levels (0.24) due to fuel dilution with 20 percent biodiesel. The cetane number of baseline fuel was 46. Adding biodiesel, which improves cetane number slightly, increased cetane number for Fuels C and D to about 48. Adding about 1 percent cetane improver, DTBP, to Fuel C, raised the cetane number to 60 for Fuel E. Neither R1 nor R2 contained oxygen. Two percent DTBG was added to R1 for Fuel A and 2 percent TPM was added to R1 for Fuel B to give both fuels an oxygen level of about 0.5 percent. Fuel C, also referred to as B20, contained 20 percent biodiesel and had an oxygen level of 2.2 percent. By adding 2 percent DTBG, Fuel D had an oxygen level of 2.7 percent. Aromatics for R2 was only 13 percent, whereas, aromatics for all other fuel was nominally 35 percent.

### TABLE 1. ADDITIZED TEST FUEL BLENDS

Test Fuel	Description
A	98 % R1 + 2% di-t-butyl glycerol (DTBG)
B	98% R1 + 2% tripropylene glycol methyl ether (TPM)
C	80% R1 + 20% biodiesel
D	78% R1 + 20% biodiesel + 2% DTBG
E	80% R1 + 20% biodiesel + DTBP[a]
[a] DTBP cetane improver added for nominal 10 cetane number increase, roughly 1% by volume	

C.   Test Procedures

Emissions of interest were measured over the heavy-duty transient cycle, following procedures given in CFR Title 40 Part 86, Subpart N. The CFR outlines specific requirements for setting up the test engine and mapping the engine's full torque capabilities over its operating speed range. Engine-specific performance data are used, along with a normalized EPA transient cycle, to define a transient command cycle for test engine operation. The 20-minute transient command cycle illustrated in Figure 2 shows the rapid changes in speed and torque the engine must produce.

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TABLE 2. PROPERTIES OF TEST FUELS

Test Fuel	R1	R2	A	B	C	D	E
Fuel Code	EM-1852-F	EM-1720-F	EM-1919-F	EM-1917-F	EM-1918-F	EM-1915-F	EM-1916-F
Sulfur (XRF) ASTM D-2622	0.032	0.011	0.032	0.031	0.024	0.024	0.024
API Gravity, ASTM D-4052	35.7	38.10	35.50	35.30	34.20	34.00	34.20
Cetane Number, ASTM D-613	45.8	50.5	44.9	45.4	48.1	47.3	60.4
Flash Point, °F ASTM D-1319	172	169	171	161	177	176	179
Viscosity, 40°C, cSt ASTM D-445	2.59	2.54	2.59	2.58	2.83	2.82	2.80
Oxygen, %	0	0	0.5	0.6	2.2	2.7	2.2
Distillation, °F ASTM D-86							
IBP	367	375	355	378	373	378	166
10%	429	424	421	429	433	428	432
50%	507	489	502	504	533	536	534
90%	598	601	597	596	627	627	630
EP	638	649	633	637	647	647	651
FIA, ASTM D-1319							
Aromtics	35.7	13.1	34.9	38.2	a	a	a
Olefin	8.3	7.5	7.5	6.6	a	a	a
Saturates	56.0	79.4	57.6	55.2	a	a	a

[a] FIA test method (ASTM D-1319) does not produce accurate results for fuels containing biodiesel.
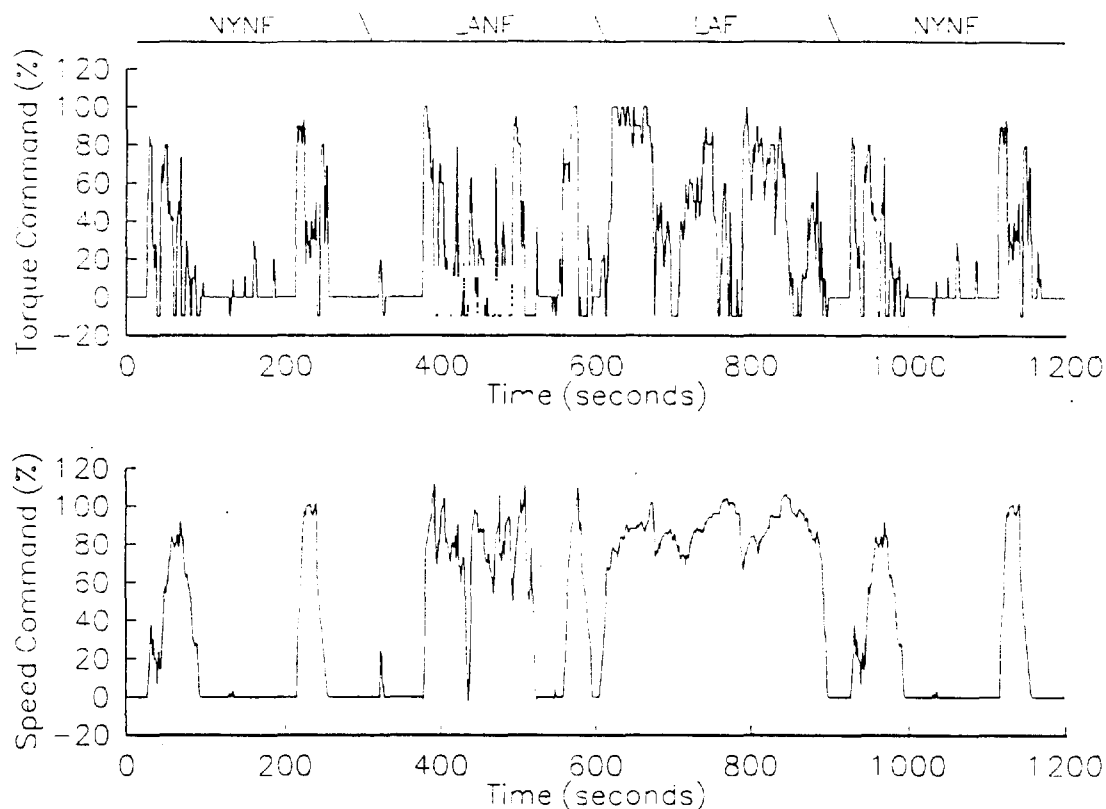
**FIGURE 2. GRAPHIC REPRESENTATION OF THE
HEAVY-DUTY TRANSIENT CYCLE**

While the engine is operated over the 20-minute test cycle, torque and speed responses of the engine are compared to the command cycle to ensure FTP compliance. Simultaneously, engine exhaust gases are diluted with conditioned air, and emissions of interest are determined. Measured emissions are divided by the level of work performed during the test, and the heavy-duty engine emissions are reported in terms of pollutant mass per unit work.

The evaluation of test fuels was carried out in a manner similar to that specified be CARB for the qualification of diesel fuels for sale in California. Only hot-start transient testing was used, with tests alternating between two fuels on any given day as follows; Fuel 1, Fuel 2, Fuel 2, Fuel 1. At each change of fuel, the fuel filter was changed and the fuel lines are drained. The engine was then warmed up on the new fuel to purge any of the remaining previous test fuel from the engine's fuel system. The engine was then torque-mapped and prepared for transient testing. Although at torque-map was run at each fuel change to evaluate engine performance, all testing was run using a transient cycle generated from the first torque-map conducted using the base 2-D fuel on the first day of testing. This was done to minimize day-to-day variability and allow for better comparison between test fuels. The sequence of fuels tested is given below in Table 3.

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TABLE 3. SEQUENCE OF HOT-START TRANSIENT EMISSION TESTING

Test Day	Fuels Tested
1	R1, A, A, R1
2	R1, A, A, R1
3	A, B, B, A
4	A, B, B, A
5	C, D, D, C
6	C, D, D, C
7	R2, E, E, R2
8	R2, E, E, R2

Emissions measured during this program included total hydrocarbons (THC), carbon monoxide (CO), oxides of nitrogen (NO_x), and particulate matter (PM). Hydrocarbons were measured using continuous sampling techniques employing a heated flame ionization detector (HFID). CO and CO_2 were determined using proportional dilute gaseous samples analyzed using non-dispersive infrared (NDIR) instruments. NO_x was measured continuously during the transient cycle via an NO_x chemiluminescence instrument. In addition, particulate samples were collected and analyzed to determine the soluble organic fraction (SOF), and the level of sulfates in the particulate. Sampling and analysis were performed on all tests to measure emissions of aldehydes and ketones. Selected bag samples were also analyzed for speciation of the C_1 to C_{12} exhaust hydrocarbons.

Speciated hydrocarbon emissions ranging from C_1 to C_{12} were determined by analyzing proportional bag samples of dilute exhaust using a series of gas chromatographs, each optimized for a specific carbon number range. Aldehyde and ketone emissions were determined using a 2,4-dinitrophenylhydrazine (DNPH) technique outlined in CFR 40 Subpart N for methanol engines. Total PM levels were determined by collecting particulate matter on a set of 90mm Pallflex filters which were weighed both before and after the transient test. Soluble organic fraction (SOF) was determined by analyzing particulate samples collected on the 90mm filters. SOF analysis was conducted according to CARB procedures, which specify the use of a toluene-ethanol mixture as the solvent. Sulfates were determined by analyzing samples of particulate collected on 47mm Fluoropore filters with an ion chromatograph.

III. TEST RESULTS

Installation of the test engine in transient Cell 3 was completed on October 25, 1994. Transient emission results are summarized in Table 4. Printouts of individual transient test results are given in Appendix A. Hydrocarbon speciation data are given in Appendix B. The initial transient-torque map using Fuel R1 was saved in the test cell computer and the transient cycle generated from that map was used to run all subsequent transient tests. This initial torque-map is shown in Figure 3. Engine performance was close to specified levels and the engine had no difficulty running the transient cycle. None of the fuels caused any significant changes in engine performance and maximum power ranged from 357 to 364 hp for fuel rates of 114 and 116 pounds per hour, respectively.

Transient emissions results for all test fuels are depicted in Figure 4 for HC and CO, and Figure 5 for NO_x and particulates. Figure 6 depicts transient emissions versus fuel oxygen content for all fuels; while Figure 7 shows emissions versus cetane number Average hot-start transient emission levels observed with Fuel R1 (baseline 2-D) were within 1991 EPA standards for on-highway trucks. Figure 8 shows the composition of total particulates for all test fuels. Analysis of the particulate filters with Fuel R1 indicated that about one-third of the total particulates were found in the SOF, while most of the remainder was carbon soot. Sulfate emissions were very low, which was not surprising considering the low sulfur content of the baseline fuel (about 0.035 weight percent).

Figure 9 shows a comparison of the five additized fuel blends in terms of percent reduction in emissions compared to Fuel R1. Fuel A was blended with DTBG, which is an oxygenate produced by the glycerine by-products of biodiesel production. At a 2 percent treat level, Fuel A contained about 0.5% oxygen by weight. The test results indicated about a five (5) percent drop in hot-start PM and HC emissions, compared to Fuel R1. No other emissions were affected in any significant way by switching to Fuel A. Particulate analysis indicated that reduction in the carabon soot portion occurred, while the SOF and sulfate levels were unchanged from the levels observed for Fuel R1. Hydrocarbon speciation indicated a small increase in formaldehyde emissions with DTBG in Fuel A, but otherwise, none of the other measured toxic or reactive hydrocarbon species were affected.

Fuel B used a different oxygenate, TPM, but the oxygen content in the blend was very similar to that of Fuel A. Transient emission results indicated that Fuel B performed much the same as Fuel A in terms of emissions, although Fuel B did show a larger decrease in HC than Fuel A. The particulate reduction was about 3.5 percent with Fuel B, compared to Fuel R1. The slight reduction in PM occurred mostly in the carbon soot portion of the total particulates. Fuel B had no significant effect on any emissions other than particulate and HC.

Fuel C contained 20 percent biodiesel by volume and is generally referred to as "B20". This fuel had an oxygen content of slightly over 2 percent by weight. Transient emission results indicated that Fuel C had a much greater effect on emissions than either Fuels A or B. Hot-start particulates were reduced by 9 percent, and CO was reduced by almost 10 percent. HC and NO_x showed no significant change. This last result was surprising in that the use of 20 percent biodiesel by volume will often cause a small increase in NO_x emissions

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TABLE 4. SUMMARY OF HOT-START TRANSIENT EMISSION RESULTS

| Test Number	Test Day	Fuel	Transient Emissions (g/hp-hr)				SOF g/hp-hr	Sulfate g/hp-hr	BSFC lb/hp-hr	Work [a] hp-hr
			HC	CO	NO$_x$	PM				
R1-1	1	R1	0.08	2.23	4.622	0.224	0.069	0.003	0.382	25.1
A-1	1	A	0.09	2.26	4.755	0.206	0.068	0.003	0.384	25.28
A-2	1	A	0.09	2.23	4.746	0.207	0.066	0.003	0.386	25.2
R1-2	1	R1	0.072	2.314	4.789	0.224	0.072	0.003	0.394	24.59
R1-3	2	R1	0.074	2.215	4.651	0.215	0.065	0.003	0.384	25.14
A-3	2	A	0.078	2.220	4.712	0.204	0.071	0.003	0.387	25.09
A-4	2	A	0.086	2.191	4.682	0.210	0.067	0.003	0.377	25.09
R1-4	2	R1	0.082	2.257	4.648	0.220	0.062	0.002	0.383	25.17
R1-5	2	R1	0.079	2.275	4.684	0.215	0.060	0.003	0.379	25.16
A-5	3	A	0.080	2.245	4.553	0.211	0.063	0.003	0.388	25.27
B-1	3	B	0.076	2.287	4.704	0.212	0.061	0.003	0.397	25.25
B-2	3	B	0.083	2.227	4.676	0.212	0.066	0.003	0.403	25.23
A-6	3	A	0.090	2.215	4.605	0.209	0.056	0.003	0.385	25.03
A-7	4	A	0.065	2.260	4.640	0.218	0.070	0.003	0.396	25.08
B-3	4	B	0.061	2.245	4.634	0.213	0.066	0.003	0.393	25.19
B-4	4	B	0.074	2.219	4.688	0.213	0.058	0.003	0.395	25.17
A-8	4	A	0.088	2.283	4.720	0.209	0.063	0.002	0.394	25.15
C-1	5	C	0.149	2.079	4.693	0.200	0.082	0.002	0.402	25.09
D-1	5	D	0.131	1.996	4.689	0.190	0.087	0.002	0.399	25.15
D-2	5	D	0.122	2.027	4.713	0.189	0.083	0.002	0.402	25.15
C-2	5	C	0.100	2.063	4.676	0.195	0.078	0.002	0.402	25.15
C-3	6	C	0.089	2.084	4.644	0.215	0.079	0.002	0.403	25.09
D-3	6	D	0.091	2.054	4.527	0.199	0.078	0.002	0.399	25.19
D-4	6	D	0.091	2.048	4.575	0.196	0.080	0.002	0.400	25.17
C-4	6	C	0.075	2.058	4.628	0.196	0.076	0.002	0.397	25.14
R2-1	7	R2	0.080	2.211	4.074	0.236	0.071	0.001	0.388	25.09
E-1	7	E	0.071	1.838	4.370	0.209	0.073	0.002	0.399	25
E-2	7	E	0.063	1.847	4.344	0.204	0.069	0.002	0.408	24.98
R2-2	7	R2	0.084	2.145	4.204	0.220	0.064	0.001	0.383	25.15
R2-3	8	R2	0.090	2.120	4.227	0.220	0.070	0.001	0.384	25.03
E-3	8	E	0.077	1.728	4.363	0.193	0.060	0.003	0.388	25.06
E-4	8	E	0.079	1.780	4.470	0.194	0.064	0.003	0.400	25.03
R2-4	8	R2	0.093	2.100	4.211	0.217	0.063	0.001	0.385	24.96
C-5	9	C	0.078	2.021	4.591	0.200	0.066	0.002	0.407	24.93
C-6	9	C	0.081	2.007	4.634	0.192	0.071	0.002	0.402	24.98

[a] Reference work is 25.61 hp-hr.

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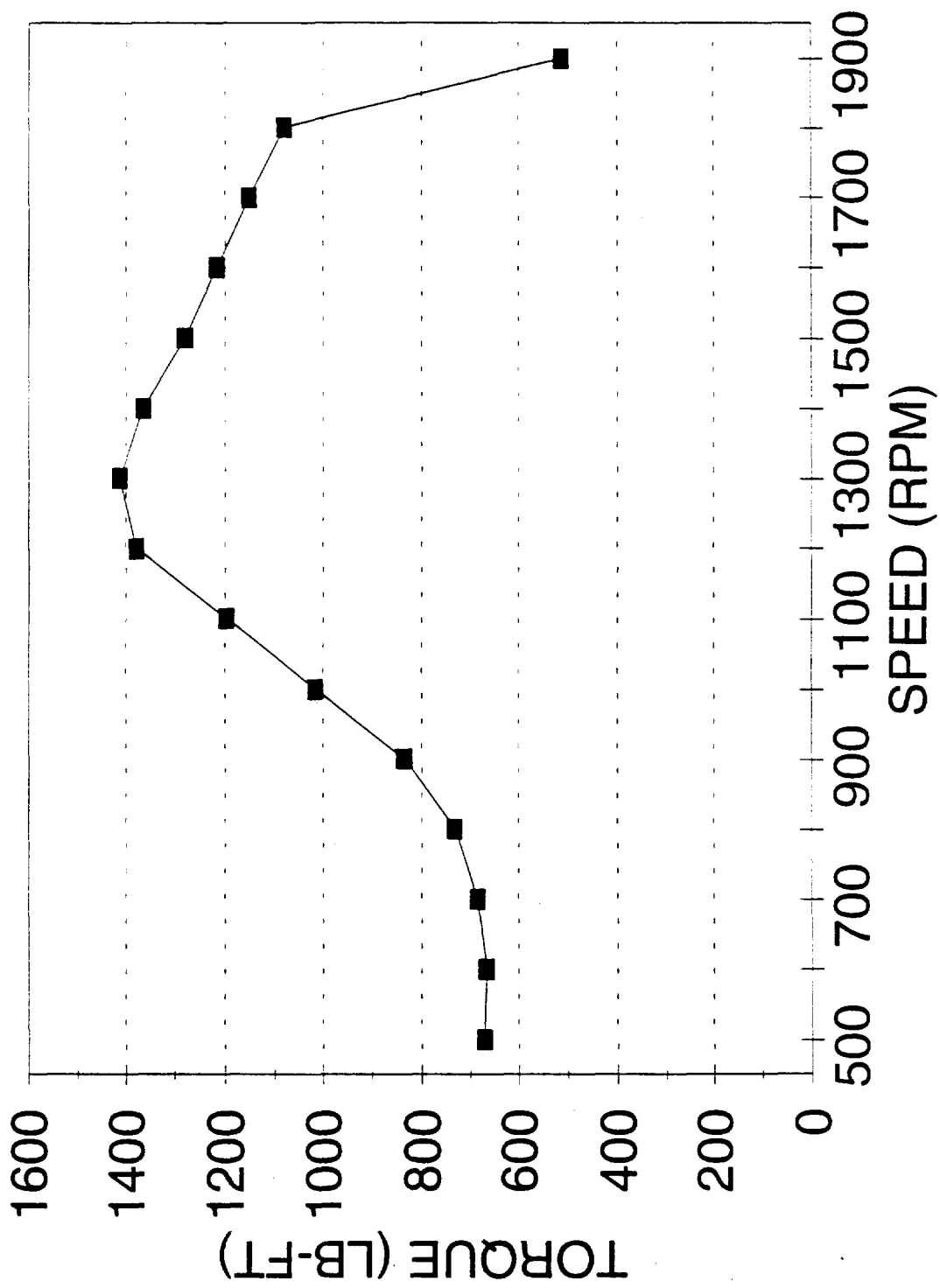
FIGURE 3. REFERENCE TRANSIENT TORQUE-MAP FOR REBUILT
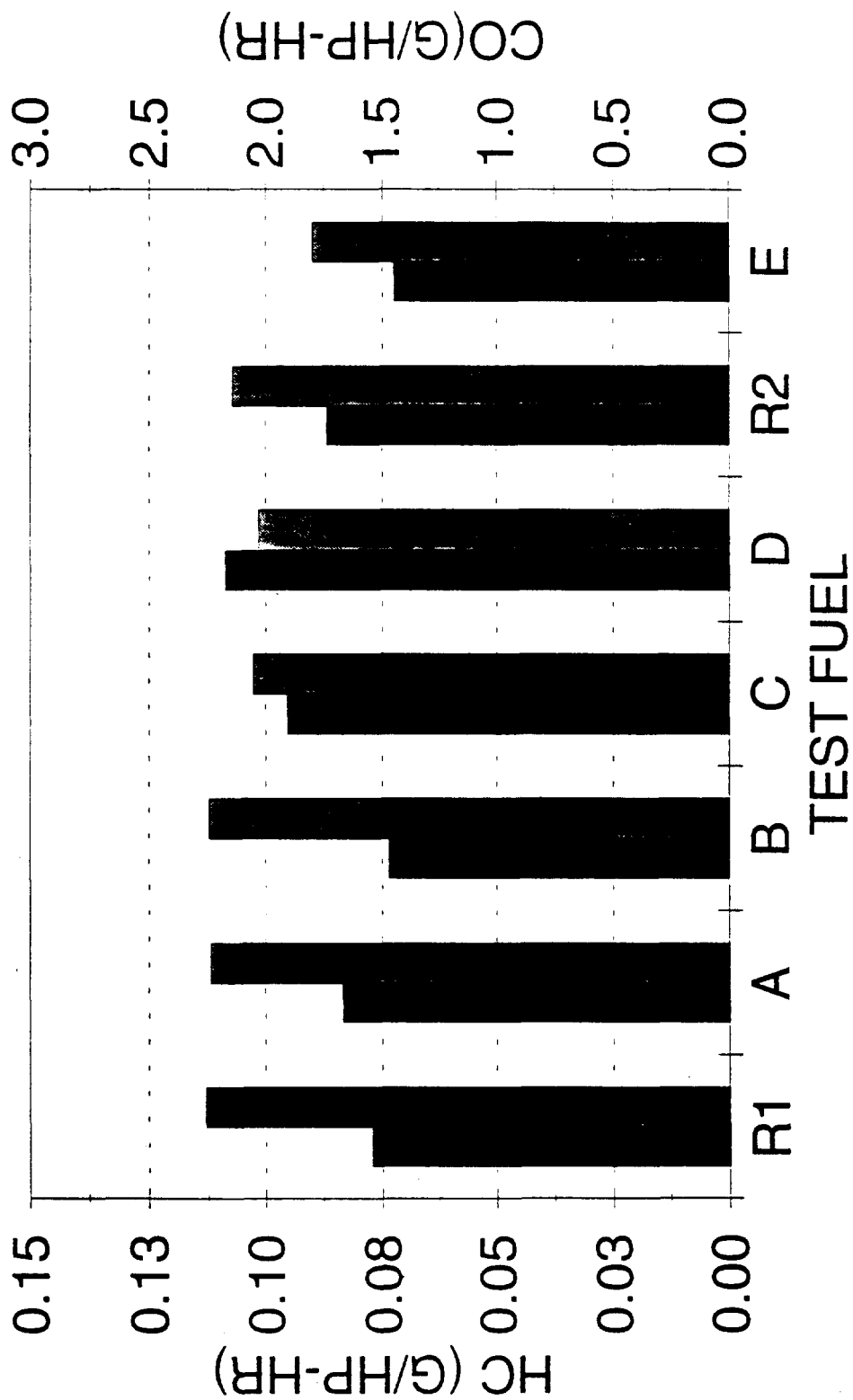1991 DDC SERIES 60 ENGINE

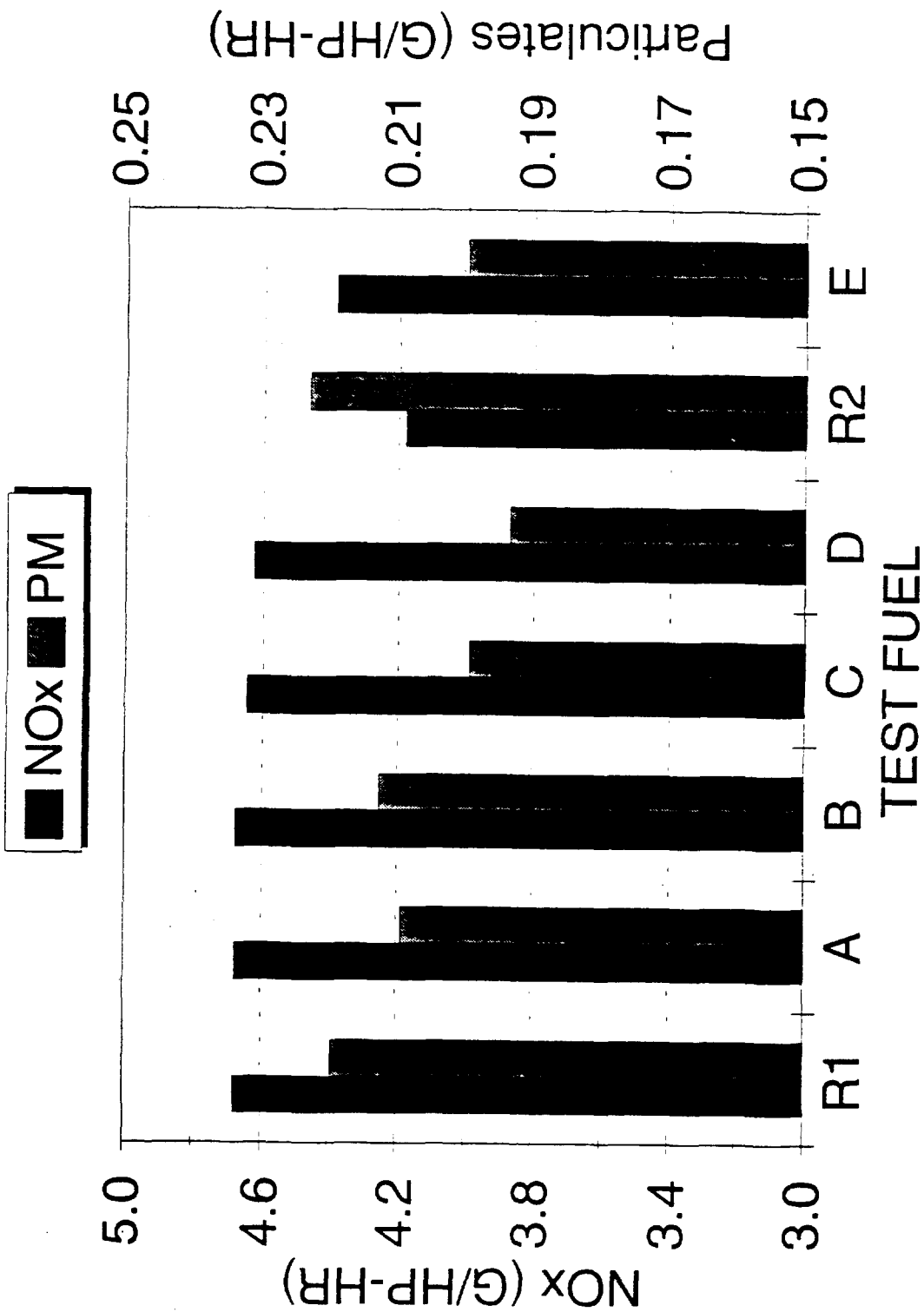FIGURE 4. AVERAGE HOT-START HC AND CO EMISSIONS
FOR ALL TEST FUELS

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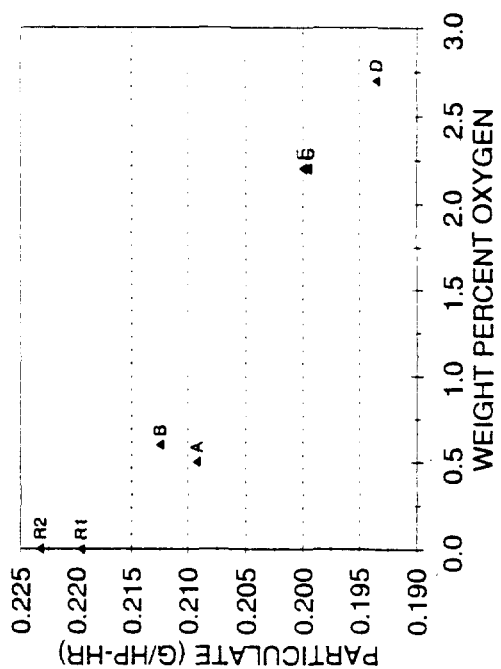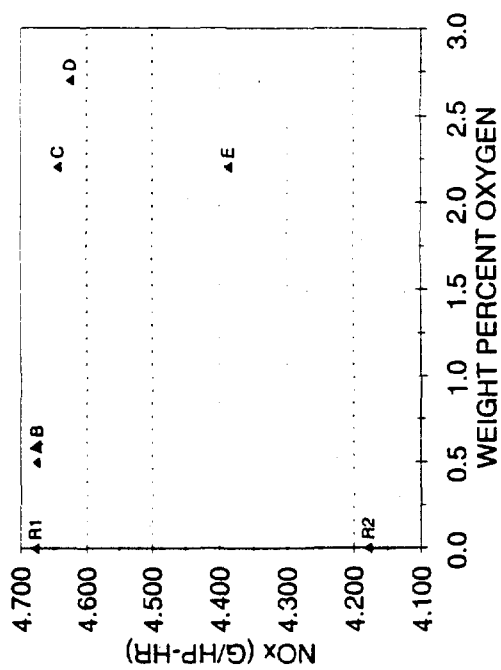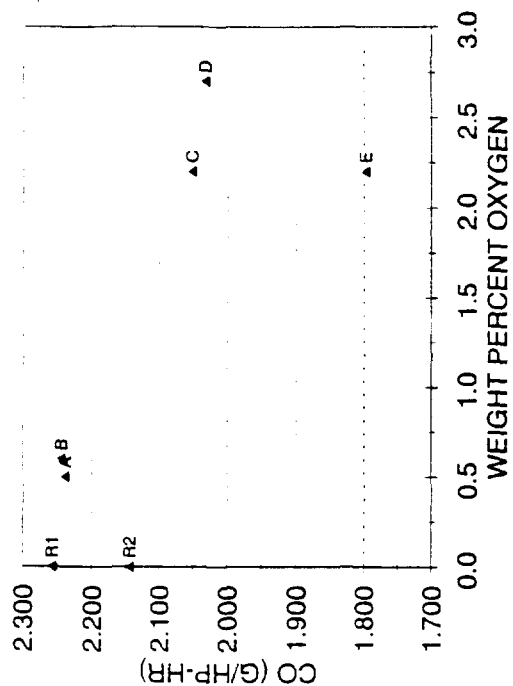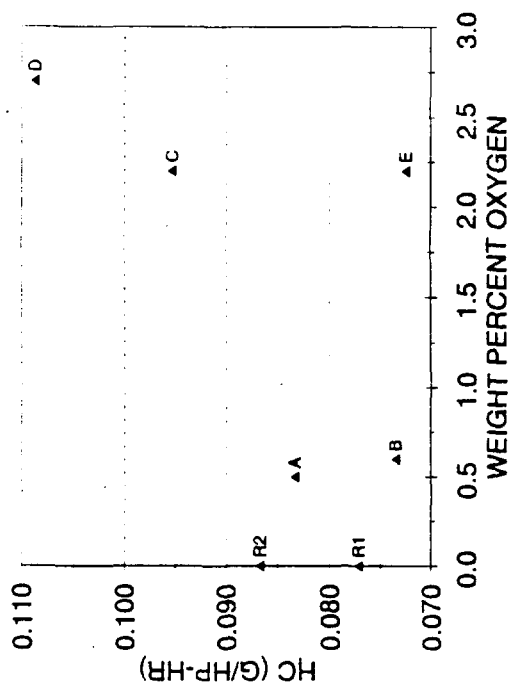FIGURE 5. AVERAGE HOT-START NO$_x$ AND PARTICULATE EMISSIONS FOR ALL TEST FUELS
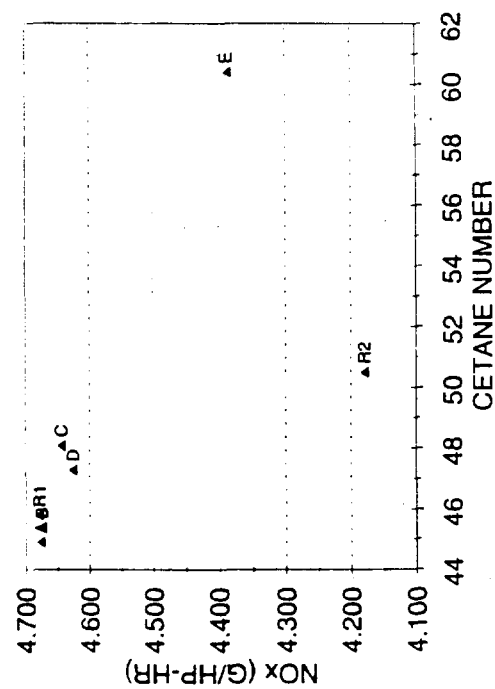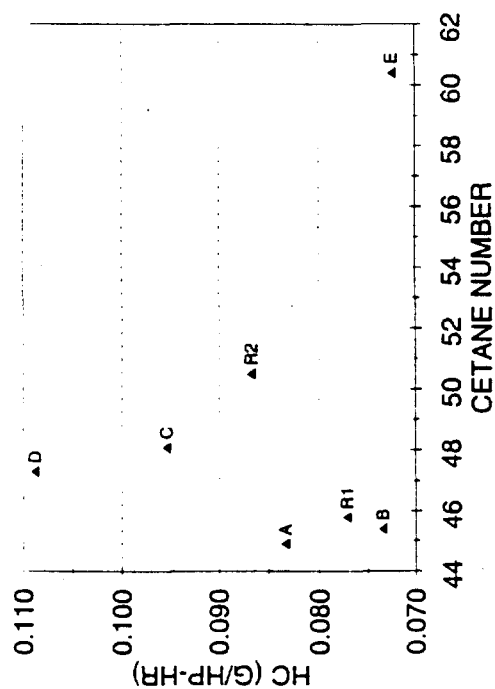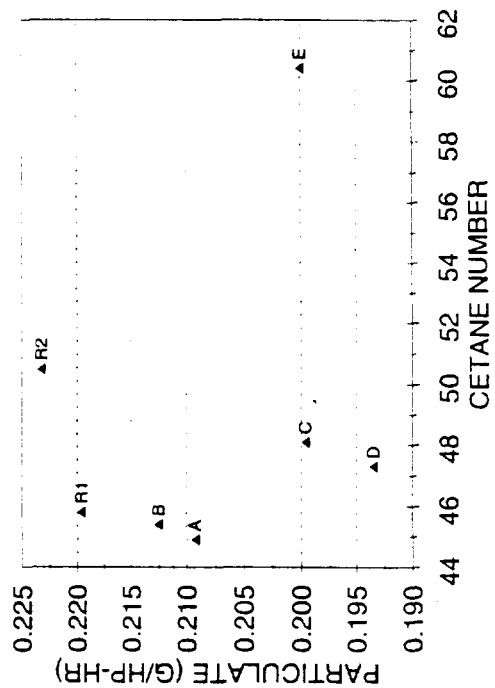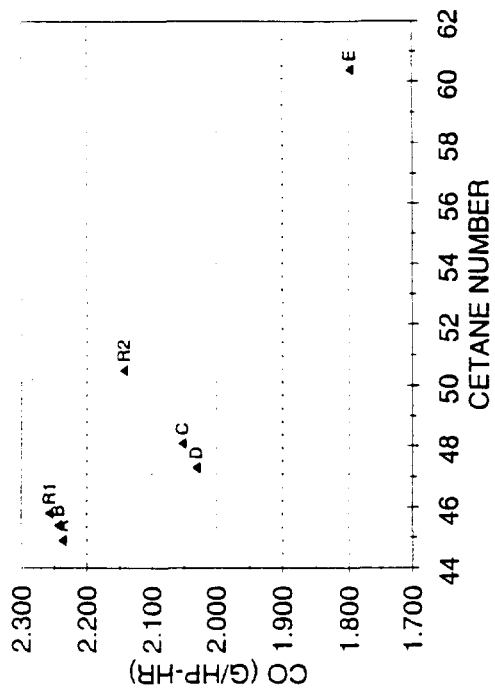
FIGURE 6. HOT-START TRANSIENT EMISSIONS VESUS OXYGEN CONTENT

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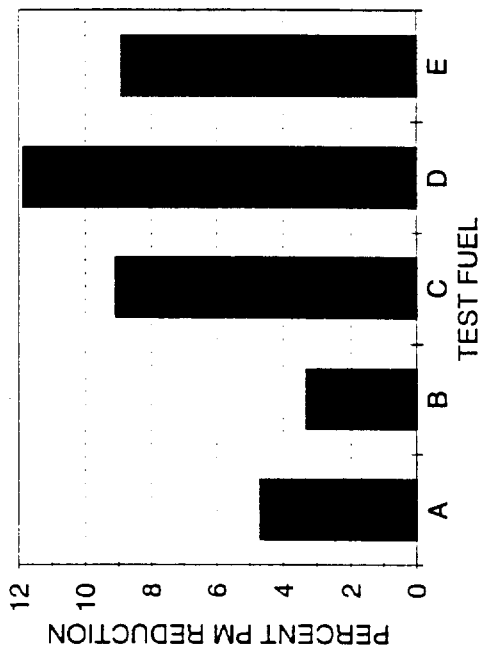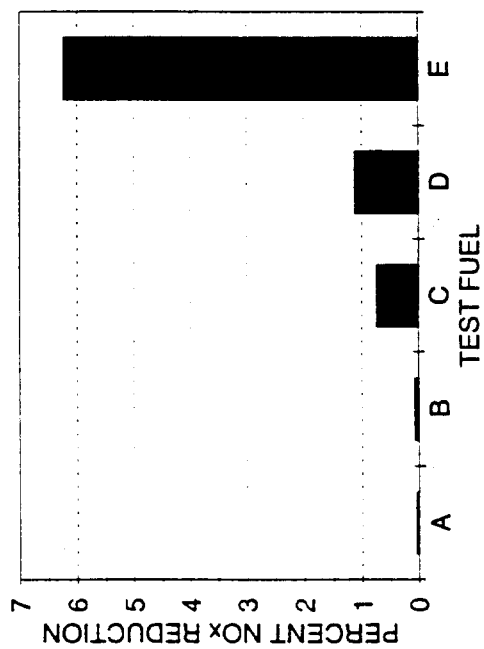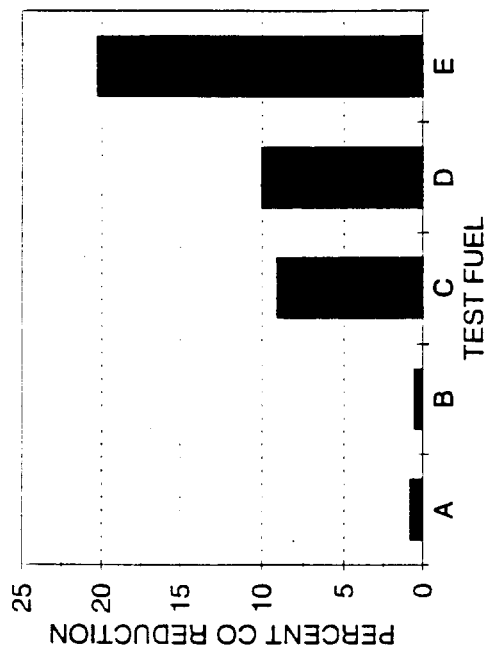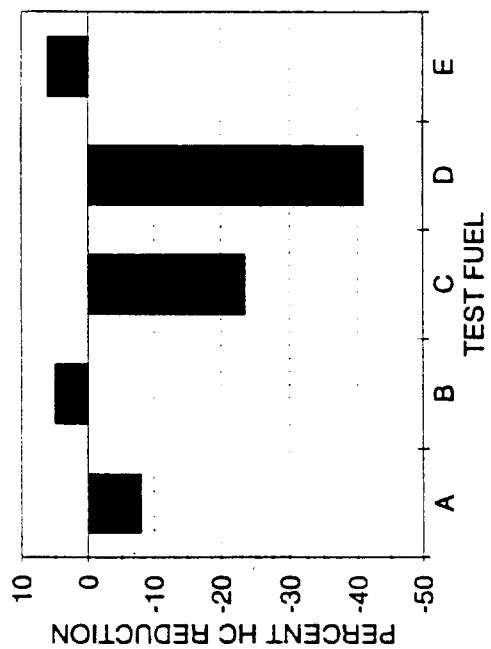FIGURE 7. HOT-START TRANSIENT EMISSIONS VESUS CETANE NUMBER

13
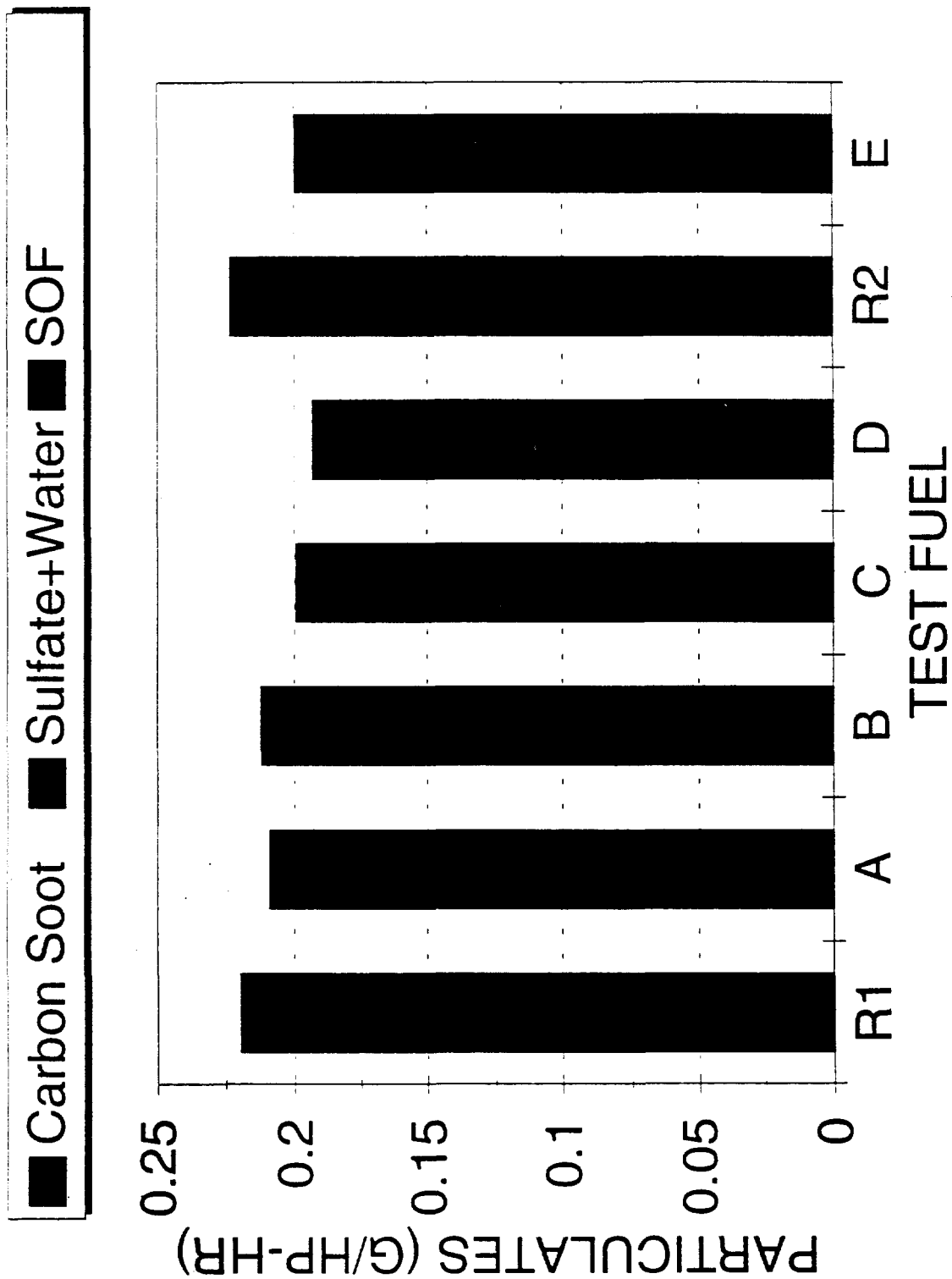
FIGURE 8. HOT-START PARTICULATE COMPOSITION FOR ALL TEST FUELS

FIGURE 9. COMPARISON OF HOT-START EMISSIONS, ADDITIZED FUELS VS. REFERENCE FUEL R1

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in other engines. Analysis of the total particulates indicated that using Fuel C caused a 20 percent decrease in the carbon soot portion, but that it increased the soluble portion (SOF) by 15 percent. These effects on particulate composition are typical of using B20. Hydrocarbon speciation indicated that no significant changes in hydrocarbon species occurred, compared to Fuel R1.

Fuel D was also B20, but it also contained 2 percent DTBG. The oxygen content of this blend was 2.7 percent by weight. Transient emissions results indicated that Fuel D reduced particulates by about 12 percent from the Fuel R1 level. This was a slightly greater reduction than observed for Fuel C, which is likely a response to the higher oxygen content of Fuel D compared to Fuel C. Similarly, the particulate reduction for Fuel D was attributed solely to a reduction in the carbon soot fraction of the total particulate because SOF was higher compared to the level for Fuel R1. In terms of gaseous emissions, Fuel D performed almost identically to Fuel C for CO and NO_x while HC appeared to be slightly higher. Speciation of the gaseous hydrocarbons did not indicate any noticeable changes in hydrocarbon species.

Fuel E was a B20 blend that contained a cetane improver, DTBP. This cetane improver was added to achieve a nominal 10 cetane number increase over the B20 fuel (Fuel C) alone. In fact, the actual cetane increased from 48 to 60, for Fuels C and E, respectively. Transient emissions tests indicated that Fuel E achieved reductions, compared to Fuel R1, in CO, NO_x, and PM of 20, 6, and 9 percent, respectively, and had no significant effect on HC emissions. Relative to particulate emissions with Fuel R1, analysis of the particulate indicated that the particulate reductions occurred due to a reduction in the carbon soot fraction, although a slight increase in SOF was also observed. Relative to particulate emissions with Fuel C, particulate analysis indicate that the addition of cetane improver to B20 did not alter that fuel's effect on total particulate level, but it reduced the SOF portion and increased the carbon soot portion slilghtly. In addition, the cetane improver caused significant NO_x reduction, as well as a greater reduction in CO than B20 alone produced. This level of NO_x reduction with a cetane increase of roughly 10 numbers of a base diesel fuel is not unusual for Series 60 engines.[1] Speciation results indicated that cetane-improved B20 was identical to "normal" B20, in that no changes in detected hydrocarbon species were was noted.

The engine was also tested with a low aromatic diesel fuel, Fuel R2, which was intended to approximate a California reference fuel. As shown in Figure 5, Fuel R2 had the lowest level of NO_x, but had a slightly higher particulate level compared to Fuel R1. Figure 10 compares the five candidate fuel to Fuel R2 in terms of percent reduction in emissions. All of the blended or additized fuels had lower particulate than. However, none of the fuels were able to match the low NO_x level of the low aromatic fuel, Fuel R2, although Fuel E had a NO_x level only about 5 percent higher than for Fuel R2. Speciation data indicated that, compared to Fuel R1, Fuel R2 had lower aldehyde emissions, but was otherwise very similar to R1.

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[1]Ullman, T. L., R. L. Mason, D. A. Montalvo, "Effects of Fuel Aromatics, Cetane Number, and Cetane Improver on Emissions from a 1991 Prototype Heavy-Duty Diesel Engine," SAE Paper 902171, October 22-25, 1990.
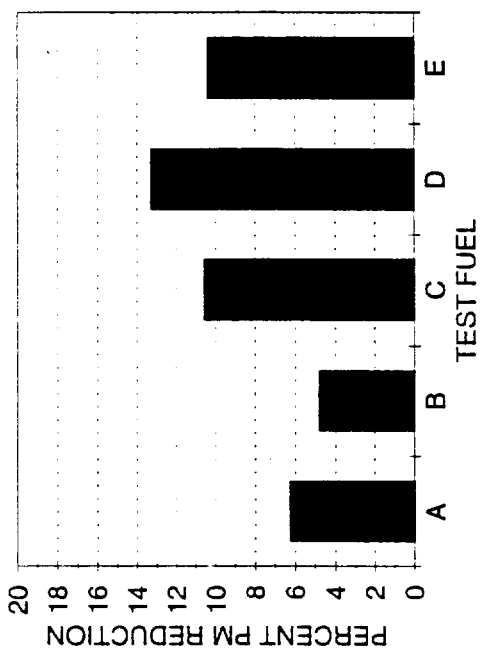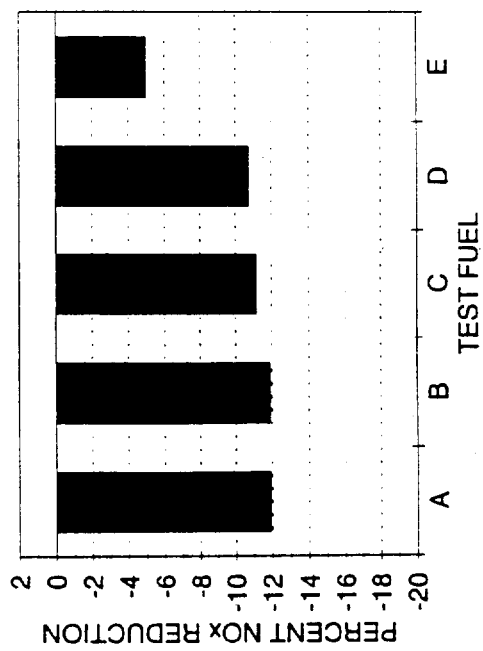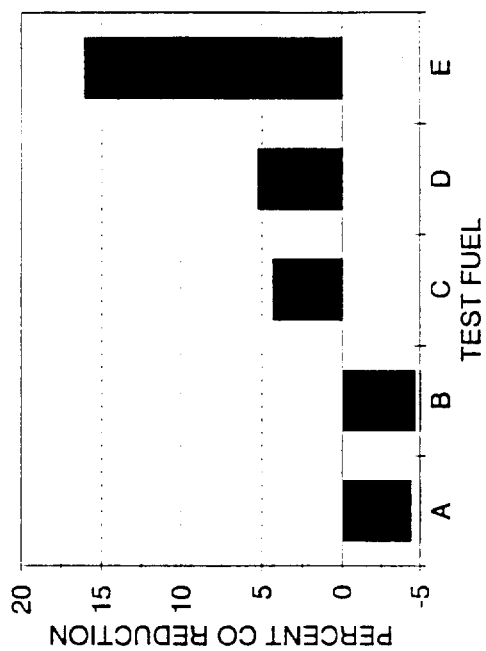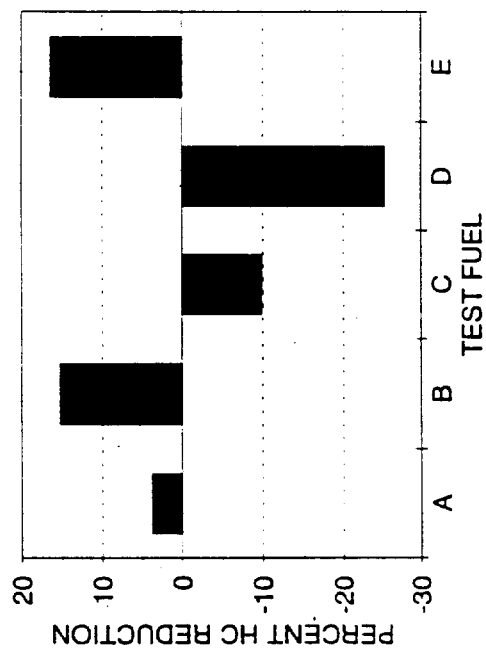
FIGURE 10. COMPARISON OF HOT-START EMISSIONS, ADDITIZED FUELS VS. REFERENCE FUEL R2

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IV. SUMMARY AND CONCLUSIONS

Five different test fuels were evaluated in comparison to both a typical low-sulfur 2-D diesel fuel, and a low aromatic, low-sulfur diesel fuel. Regulated emissions of HC, CO, NO_x, and particulate were measured, as well as unregulated emissions of SOF and sulfate. On selected test runs of each fuel, C_1 to C_{12} speciation was performed to characterize the composition of gaseous HC emissions.

All of the five test fuels contained some level of oxygenate. In general, all of five fuels performed as expected, that is, reducing particulates and CO. The amount of these reductions were proportioned to the total weight percent of oxygen present in the fuel, except when cetane improver was present. The level of particulate reduction ranged from 3 to 12 percent, and oxygen ranged from 0.5 to 2.7 percent by weight. CO showed a similar relationship with varying oxygen content. HC emissions tended to increase with B20, yet NO_x tended to decrease slightly. Speciated hydrocarbon emissions were not greatly affected by any of the oxygenates.

The combination of B20 and DTBP cetane improver produced substantially lower NO_x, CO and lower particulates than the 2-D baseline fuel. The low aromatic diesel fuel had the lowest NO_x level of all the fuels run, but it had higher particulate emissions than the baseline 2-D fuel. All of the oxygenated fuels had lower particulate emissions than the low aromatic fuel, but higher NO_x levels. The cetane-improved B20 came close to matching the low NO_x levels noted for the low aromatic fuel. Further modification of cetane improved B20 would be needed in order to match the emission levels of a low aromatic low-sulfur California fuel.